Surface Effects in Magnetic Microtraps

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We have investigated Bose-Einstein condensates and ultra cold atoms in the vicinity of a surface of a magnetic microtrap. The atoms are prepared along copper conductors at distances to the surface between 300 μm and 20 μm. In this range, the lifetime decreases from 20 s to 0.7 s showing a linear dependence on the distance to the surface. The atoms manifest a weak thermal coupling to the surface, with measured heating rates remaining below 500 nK/s. In addition, we observe a periodic fragmentation of the condensate and thermal clouds when the surface is approached.

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Micropotentials have proven to be a powerful tool to manipulate and structure the shape of a Bose-Einstein condensate [1] on a length scale shorter than the coherence length of the condensate. Besides the manipulation with light [2, 3, 4, 5, 6], current carrying microstructures [7] are particularly interesting since they can be tailored in an arbitrary way, providing a variety of potential geometries. In previous experiments with magnetic microtraps the work was mainly focused on the demonstration of different trapping geometries, loading schemes and guiding principles [8, 9, 10, 11, 12, 13, 14]. The recent realization of Bose-Einstein condensates in magnetic microtraps [15, 16] however provides new possibilities to control coherent matter on the micrometer scale. Coherent beam splitters, on-chip interferometers or quantum dots may become feasible. In current experimental setups, the dimensions of the conductors vary from 1 μm to 100 μm and the distance between the trap minimum and the surface is typically of the same size. At such small distances the atoms are affected by the nearby surface. For experiments with coherent matter waves or even single atoms in microfabricated traps an understanding of the mutual influences of the atoms and the surface is highly desirable.

In this letter, we describe three effects on ultra cold atoms which appear in the vicinity of the surface of a magnetic microtrap. We observe a decrease of the lifetime of the atomic cloud which scales roughly linearly with the distance to the surface. At 20 μm, the lifetime is reduced to less than 1 s, which has to be compared to the "far distance" value of 100 s. Simultaneously, an increased heating rate is observed which, however, does not exceed 500 nK/s. Furthermore, a periodic fragmentation of both, the thermal cloud and the condensate occurs when the surface is approached at distances of about 250 μm. This gives strong evidence for additional potentials arising from the nearby surface.

In our experiment, the microtrap is generated by a microstructure which consists of seven parallel copper conductors with widths of 3 μm, 11 μm and 30 μm, a height of 2.5 μm and a length of 25 mm [17]. The conductors are electroplated on an Al_2O_3 ceramic substrate. An additional copper wire with a circular diameter of 90 μm is mounted parallel to the microstructure, allowing for reference measurements. The free surface of the wire is in the plane of the fabricated conductors. The radial potential is built from the field of one of the eight conductors with current I and a homogeneous bias field B_{bias} perpendicular to the conductor. The axial confinement is accomplished by a superimposed Ioffe type trap [18], that also provides a non-vanishing field B_0 in the centre of the trap. The axial oscillation frequency has an upper limit of $2\pi\times 14$ Hz and can be tuned without affecting the radial confinement by changing the strength of the Ioffe type trap. In all experiments, a pre-cooled cloud of ^{87}Rb atoms in the $|F=2, m_F=2>$ hyperfine ground state is transferred into the microtrap. The loading procedure, the adiabatic transfer, and the experimental cycle are described in detail elsewhere [15]. The trap geometry is characterized by its axial and radial oscillation frequency ω_a and ω_r, and by its distance d to the surface. Assuming a linear conductor carrying current and a homogeneous bias field perpendicular to the conductor, ω_r and d are given by

$$\omega_r = 2\pi \times \frac{1}{\mu_0}\sqrt{\frac{\mu_B g_F m_F}{m B_0}} \times \frac{B_{\mathrm{bias}}^2}{I},$$

$$d = \frac{\mu_0}{2\pi} \times \frac{I}{B_{\mathrm{bias}}},$$

where m denotes the mass of the atom. For a given distance d and a radial oscillation frequency ω_r the current I in the conductor and the required bias field B_{bias} are fully determined. Thus, the radial steepness of the waveguide and its distance to the surface can be tuned independently.

To investigate lifetime and heating rate we prepare cold thermal ensembles at different distances to the trap surface. The temperature is adjusted to 2 μK, well above the critical temperature for Bose-Einstein condensation. The trap is kept constant for a variable storage time and the number of atoms as well as the temperature are determined from time of flight measurements of the released

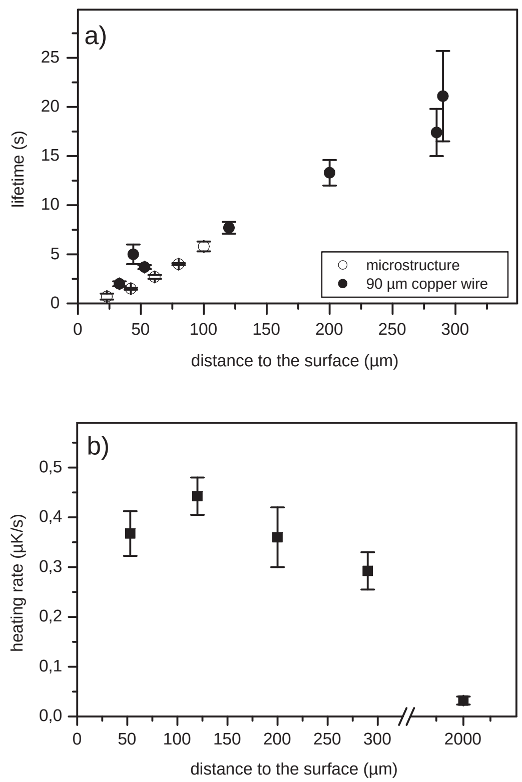

FIG. 1: Lifetime and heating rate of thermal atoms in the vicinity of the surface ($T = 1.5$ μK). a) Lifetime near the surface of the microstructure and the 90 μm wire. The lifetime for a distance of 2 mm is $100s$. b) Heating rate at the 90 μm copper wire. Measurements at the microstructure yield to similar results. The last data point on the right is taken at a distance of 2 mm.

atomic cloud. Fig. 1a shows the measured trap lifetimes at the microstructure and at the 90 μm copper wire. The lifetime reveals a linear dependence on the distance to the conductor surface over a wide range. For small distances the data differ from a pure linear behaviour. Both types of conductor (massive copper wire and thin, electroplated conductor) show a similar influence such that close to the conductor the lifetime is reduced by two orders of magnitude. For a distance of 20 μm the measured lifetime is as short as 700 ms, whereas for a distance of 2 mm a reference value of 100 s has been determined. To bring the atoms close to the surface the current in the conductor are reduced. In this case, the dissipated heat in the conductor due to resistive heating scales as $P \propto d^4$. Thus, at smaller distances the temperature of the conductor is lower. In our experiment, the conductors are mounted on a cooled copper heat sink which provides an almost constant temperature. To avoid influences due to long-time heating of the equipment the data points for different distances to the surface were measured in random order. This allows us to exclude outgassing effects. Evaporation of cold atoms that hit the surface can also be excluded: at small distances the potential barrier at the conductors surface is approximately 6 G corresponding to a temperature of more than 400 μK. In [19] surface induced spin flip transitions are analyzed as lifetime reducing mechanism. Spin flips can be induced by the oscillating magnetic field of thermally excited currents in the metal or by technical noise at frequencies around 1 MHz. Because the radiation field of a dipolar antenna decreases inversely proportional with the distance the measured data are in qualitative agreement with the theory.

The experiments were performed on thermal atomic clouds at densities below $1 \times 10^{14}\,\mathrm{cm}^{-3}$ and no indication of inelastic processes like three body recombination [20] was observed. The generation of Bose-Einstein condensates results in higher densities and inelastic processes become important. In highly elongated traps with $\omega_a = 2\pi \times 14$ Hz and $\omega_r > 2\pi \times 1000$ Hz as used for the previous experiments, we reach condensation at densities above $1 \times 10^{15}\,\mathrm{cm}^{-3}$ and the lifetime of the condensate is limited to a few 10 ms. Longer lifetimes can be achieved if the density is reduced by adiabatic relaxation of the trapping potential. For $\omega_a = 2\pi \times 8$ Hz, $\omega_r = 2\pi \times 100$ Hz and d=300 μm we measure a condensate lifetime of 2.3 s.

The heating rate has been determined by measuring the temperature of the cloud after different storage times. Fig. 1b shows the heating rate for different distances to the surface. In all studied scenarios, the heating rate was less than 500 nK/s. For comparison, at a distance of 2 mm a reference value of 32 ± 8 nK/s has been determined, indicating an extremely low technical noise in our apparatus. Thus, the increased heating rate can be addressed to specific effects close to the conductors surface. Heating can be induced due to fluctuations of the magnetic field at the trap frequencies, at their half or harmonics, however we found no indication for such kind of noise in our experiment. Although the lifetime of atomic clouds close to the surface is significantly reduced, this puts only moderate restrictions on applications of magnetic microtraps. For a condensate the heating leads to additional losses. However, it does not necessarily reduce the coherence properties.

More important, we have observed an unexpected periodic fragmentation of the atomic cloud along the conductors at distances of less than approximately 250 μm. To study this fragmentation we have prepared a cloud of ultra cold atoms at different distances to the surface. Subsequently, the axial confinement of the trap was turned off within 400 ms and a homogeneous bias field was applied along the axial direction in order to retain the parabolic character of the radial confinement. This configuration allows for a free propagation of the atoms in the waveguide. An undisturbed propagation is observed for distances larger than 300 μm. Below 250 μm, the guiding potential obviously exhibits a significant waviness. Fig. 2 shows the distribution of a thermal cloud after 100 ms of expansion in the waveguide. The

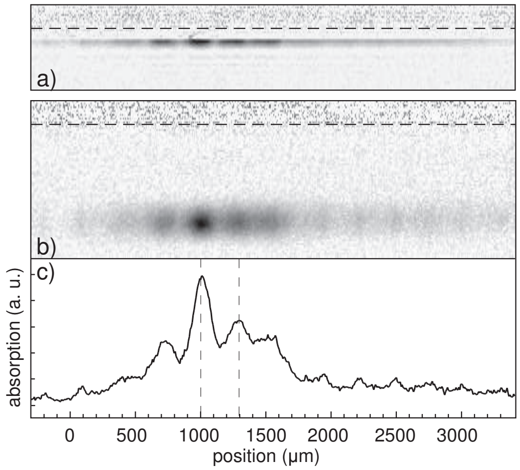

FIG. 2: Fragmentation of a thermal cloud in the vicinity of the surface ($N = 560,000$, T=1 μK). The axial confinement was ramped down to zero within 400 ms and the cloud was allowed to freely expand for 100 ms. The absorption images were taken a) in the waveguide and b) after 10 ms time of flight. c) The integrated scan shows a periodicity of 300 μm in the density distribution of the cloud along the waveguide. The radial oscillation frequency was $\omega_r = 2\pi \times 1000$ Hz and the waveguide potential was located at a distance $d = 150$ μm to the surface. The dashed line indicates the surface of the microtrap and the orientation of the conductors.

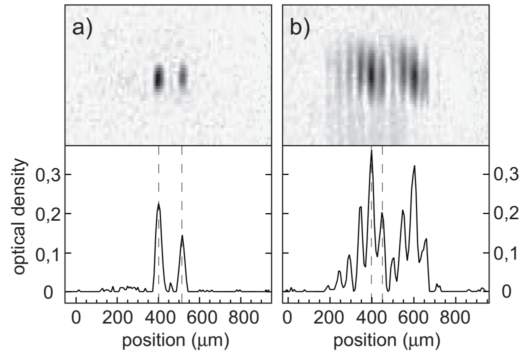

FIG. 3: Fragmentation of a Bose-Einstein condensate close to the surface. The absorption images were taken after 15 ms time of flight. a) Two condensates 300 ms after relaxation of the axial confinement. The spacing of the condensates is 110 μm ($d = 100$ μm). The condensate at the left contains 12,000 atoms, at the right 7,000 atoms. b) Multiple condensates with a periodic spacing of 50 μm ($d = 50$ μm). The condensates were released from the trap without relaxation of the axial confinement. The envelope shows a 200 μm structure which is due to the superposition of the surface potential with a period of 300 μm (Fig. 2) and the axial confinement ($\omega_a = 2\pi \times 14$ Hz) of the microtrap. The total number of atoms is 165,000, the tallest part contains 33,000 atoms.

modulation of the atomic density distribution indicates the presence of an additional periodic trapping potential generated by the microstructure. The spacing between the potential minima is 300 μm and the depth of the potential is on the order of $k_B \times 1\,\mu$K which can be estimated by the temperature of the atomic cloud. Changing the distance to the surface has no influence on the position and the period of the potential minima. Releasing a Bose-Einstein condensate in the waveguide allows for the detection of finer substructures. Fig. 3a shows two condensates with a separation of 110 μm. The image was taken 300 ms after the axial relaxation was completed and the waveguide potential was located 100 μm below the microstructure. The axial confinement of the microtrap was completely turned off and the condensates were still trapped in two potential minima at the surface. An even finer structure can be observed at a distance of 50 μm. Fig. 3b shows the formation of individual condensates with a separation of 50 μm. In this experiment, the image was taken directly after the last cooling stage in the trap without ramping down the axial confinement.

The appearance of the surface potentials can be observed at each of the seven conductors of the microstructure. Dependencies of the period and position of the potential structure have to be investigated in future experiments. The experiments were repeated at the 90 μm copper wire. Here, we observe a periodic modulation with a spacing of 220 μm including a substructure with 110 μm.

To exclude interatomic interaction as a possible reason for the separation, we have generated two neighboring condensates as shown in Fig. 4a. One of them was subsequently removed with a focused laser beam. In accordance with our assumption of periodic surface potentials the second condensate remains at the same position, whereas a fraction of the thermal cloud starts to oscillate in the trap.

Magnetic modulations caused by a transverse current variation decay on a length scale which is on the order of the transverse dimension of the conductor. Thus, modulations over larger distances can only be addressed to longitudinal variations. They cannot arise from the flow of the electric current, which has to be constant along the conductor. To exclude any material impurities like ferromagnetic domains, we have made a chemical analysis (energy dispersive X-ray analysis, EDX) of an identical microstructure, which revealed no measurable impurities [17]. Trivial causes for modulated electrostatic or gravitational potentials can be excluded. One may speculate that the observed potential modulations could be attributed to longitudinal or transversal spin arrangements of moving electrons in copper [21]. Meanwhile, the observations discussed above could be reproduced by two other groups [22, 23] working on microtraps. The common feature of the experiments is the use of copper conductors as current-carrying elements for generating the micro trap, with differences due to the various conductor profiles and currents.

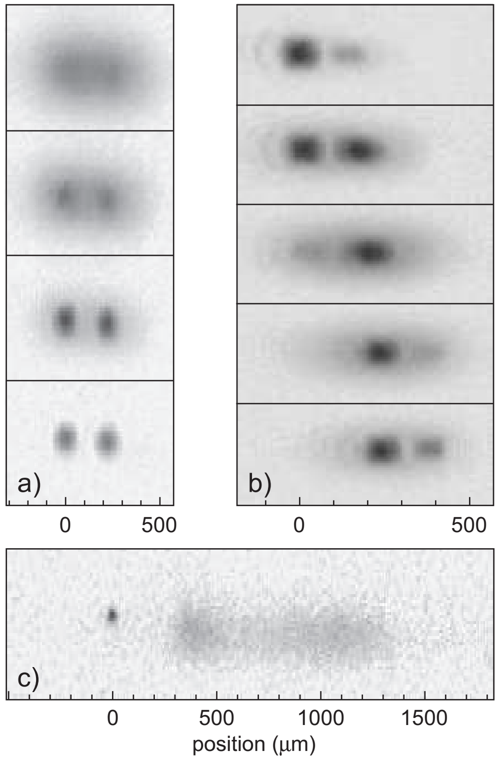

FIG. 4: Pinning of the condensates. a) Simultaneous formation of two condensates at a distance $d = 150$ μm to the surface. The superposition of the surface potential and the axial confinement of the trap results in a spacing of 220 μm between the two potential minima. The images were taken at different temperatures below T_c after 15 ms time of flight. The critical temperature is reached with 500,000 atoms (first image), the condensates contain 65,000 atoms each. b) By shifting the centre of the trap along the waveguide, the condensates populate stationary potential minima (10 ms time of flight). c) Separation of a condensate (5,000 atoms) and the thermal cloud (90,000 atoms) after 100 ms of free expansion in the waveguide (15 ms time of flight).

The appearance of additional potentials at the surface has several consequences for the application of magnetic microtraps for Bose-Einstein condensates. A continuous shift of the condensate along the conductor or an undisturbed propagation in a waveguide is only possible at a sufficiently large distance to the surface. Fig. 4b shows a sequence of absorption images where the trapping potential was shifted in the axial direction. As a result the condensates are pinned on the periodic potential and populate subsequent potential minima. Another example for the pinning effect is illustrated in Fig. 4c. The atomic ensemble is shown after 100 ms of free axial expansion in the waveguide. The condensate remains pinned at its original position while the thermal cloud starts to propagate in the waveguide resulting in a separation of the two components.

In conclusion, we have investigated the lifetime and the heating rate of ultra cold gases in the vicinity of a surface for a set of parameters that corresponds to currently used microtrap setups. We find evidence for influences of the surface resulting in a reduction of the lifetime and an increased heating rate. The appearance of a periodic potential near the surface is a qualitatively new phenomenon which has to be investigated in future experiments.

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